Proton Board-Level Testing: Achieving Limited Radiation Assurance with Minimal Testing

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Is This Assurance Engineering?

Outline

- The best scenario
- What is board-level testing with protons?
- What are the problems?
- It has be useful… why?
- Test planning
- Test preparation
- Test execution
- Test interpretation
- Lessons Learned
- Summary

Best Use(s) of Proton Board Testing

- Remaining risk is within the mission risk profile
- When you are going to LEO
- You have exact copies of the flight board
- Your system has ~ 100 components

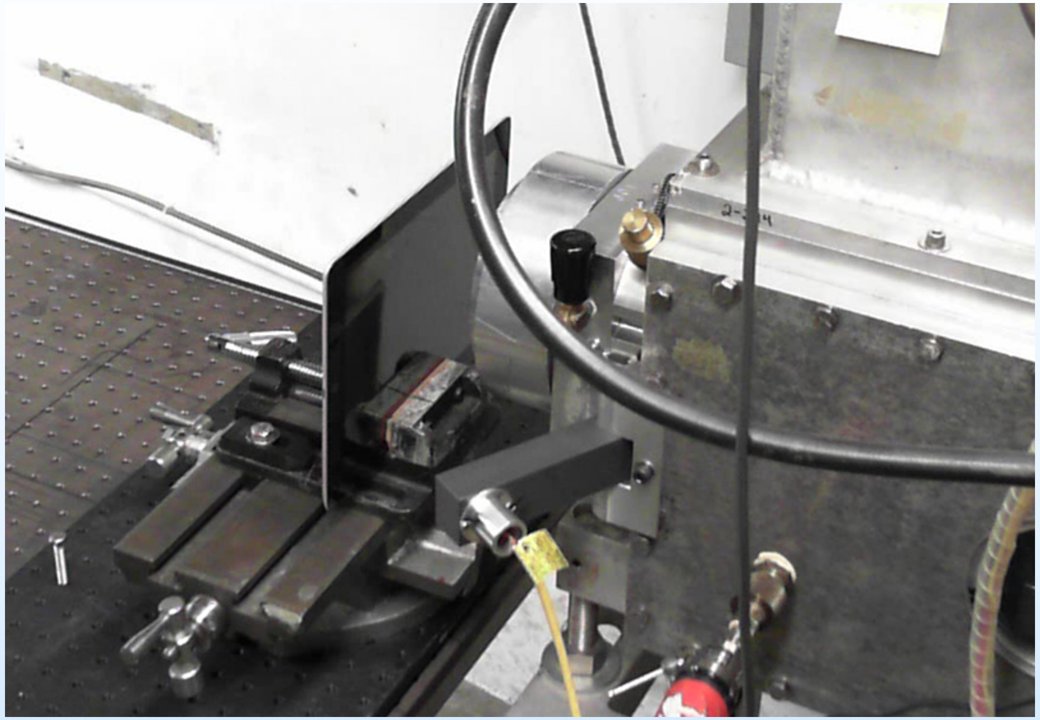
- Even then, you get limited assurance
  - No information on worst-case SEE if parameters change
  - You only get system failure rates of about 0.01/system-day – provided nothing fails during the proton test

- It's going to work best when the environment is weak
  - Fails to effectively test higher LET portions of space spectrum

NEPP Guideline

- People are testing boards, boxes, and other assemblies with only protons

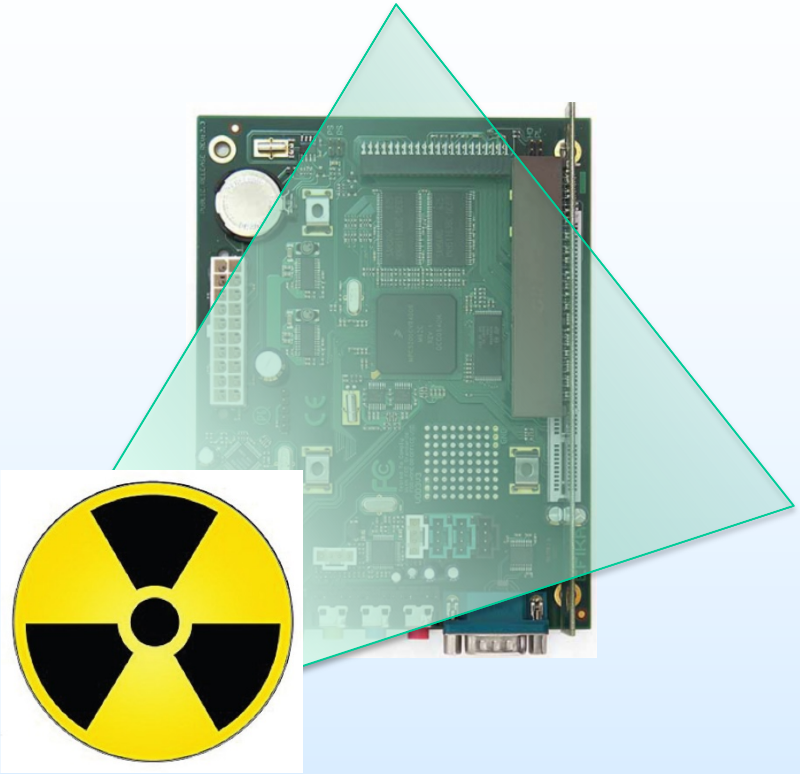
- This is of … limited value
- And there are significant ways that tests can be of even less value
- NEPP is developing a proton board-level testing guideline to help with this problem



iPad irradiation at UC Davis

- See also the NEPP low-energy proton test guideline: http://radhome.gsfc.nasa.gov/radhome/papers/MRQW2012_Pellish.pdf

Is a Board-Level Test going to Help?



vs…

- Board level tests have many issues…
- Would you be better off guessing?

And When There's a Failure?

- Do you know anything about what happened?
- Probably it will just be called an "anomaly"…

- Is the on-orbit failure worth the money you saved?

The Hard Truth

- When I first started looking at this…
- It looked a bit like a war
  - Red light people were saying it was useless – Literally you're better off not doing it because it is misleading
  - Green light people were saying it could be used to assure multi-year missions
- But, as I looked closer…
- Red/Orange light vs Yellow light.
  - The method does not assure, but it can give you an approximate failure rate.
  - How high should that failure rate be for a mission to fly?
- But some new groups on the stage were seeing the green light…

- This is more of a system validation/risk evaluation approach – gives a warm and fuzzy feeling

Board Level Testing Done Right

- If you have the right combination of
  - Mild environment
  - Short duration
  - Willingness to accept risk

- Typical environments where it might be good
  - Minimal high LET particles (ideally, very little GCR)
  - Proton-dominated, or weak radiation environment
    - LEO (especially equatorial – note that ISS is not equatorial)
    - MEO (low-LET dominated, but very high radiation)
    - Mars surface
    - Other magnetically-shielded locations

- Mission profiles
  - Very short (for example, approach to ISS ~ 10 minutes)
  - High risk tolerance
    - High redundancy, active mitigation

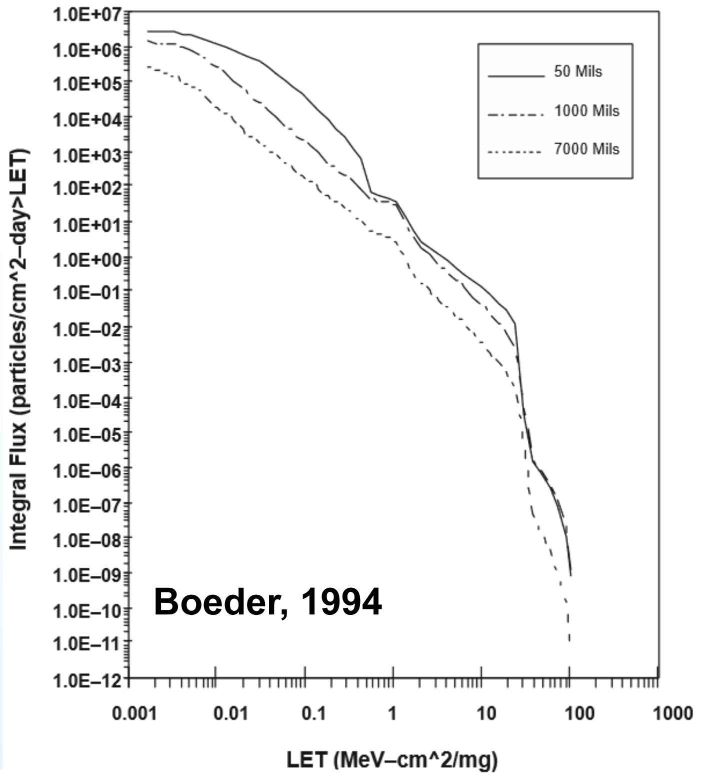
Board Level Testing Done Right

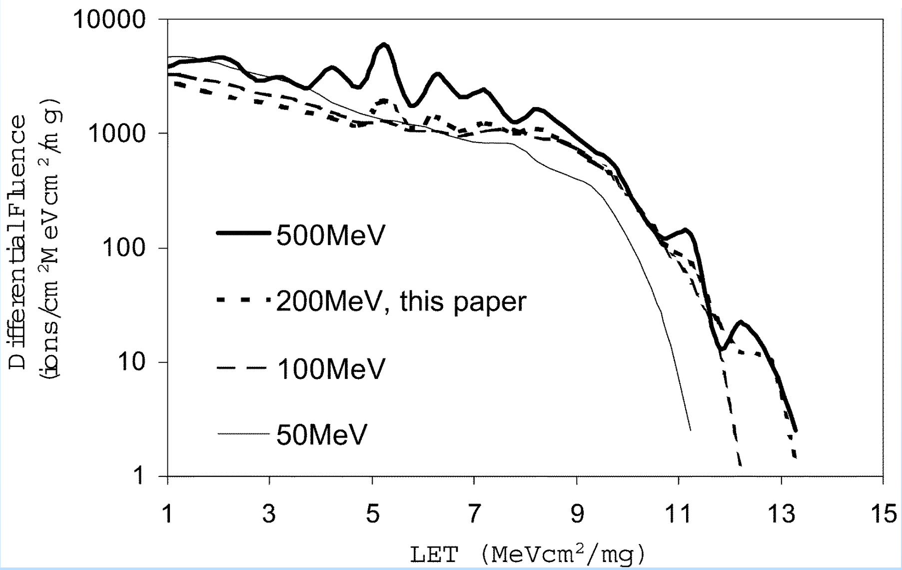
- For radiation hardness assurance, is there a simple and cheap way to:
  - Do single-event effects testing of a flight board/assembly, all at once?
  - And simulate much of the space environment at once?
  - Sort of, but you may miss a lot…

- What do you do?
  - Test with high energy (~200 MeV) protons. (Next slide…)
  - You can test multiple boards simultaneously
  - Multiple energies is best for assurance (but you need 0 events)
- How good is it?
  - Questionable – worse if done wrong. (Rest of the talk.)
  - But it does give good fault injection, similar to using neutrons to inject errors at the board level.

Space vs. Protons

- Protons generate "higher LETs" through secondaries provided by the target.
- Basic comparison is to just look at the LET generated by proton secondaries.
  - Hiemstra, and also recent work by Ladbury
- The basic comparison suggests that LETs as high as 12 MeV-cm^2/mg are tested.
  - ~20 particles/cm^2-year are above this in ISS orbit.
- But this is misleading…





Hiemstra, IEEE 2003

But Even That's Not Right

- The Sensitive Volume (SV) model says that the critical value for ion SEE is Q_c

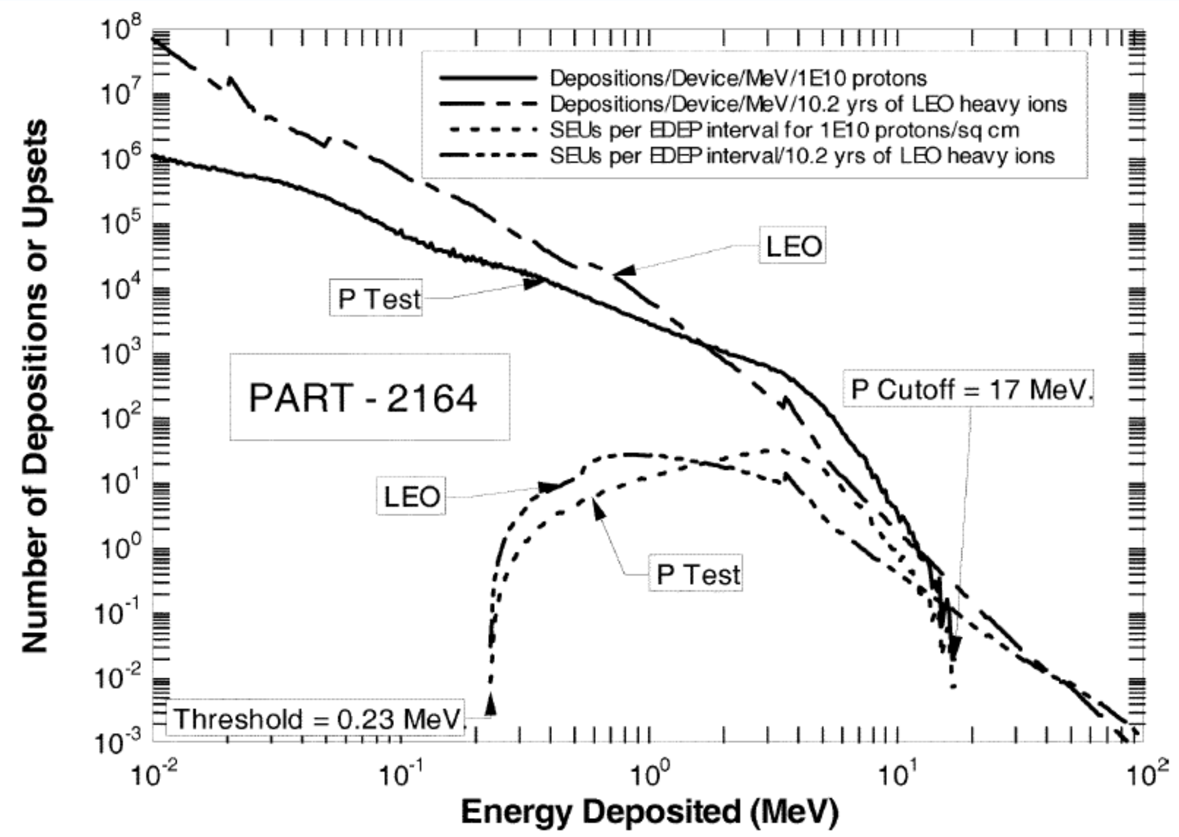
$$Q_C = \int C * LET(x)dx$$

- Proton secondaries have very limited range – usually < 20 μm
  - At best, this limits the integral.
  - This is critical for SEE types with deep charge collection, like SEL

Protons Have Limitations

- In a 2μm sensitive depth…
  - $1\times10^{10}/cm^2$ 200 MeV Protons
  - More protons can be used
- Proton recoils give energy depositions similar to heavy ions
  - But leave high energy deposition gap
  - More protons weakly affect the gap region
- But not all SEE modes are this shallow
  - More later

Foster, IEEE TNS, 2008 – energy deposition in 2μm



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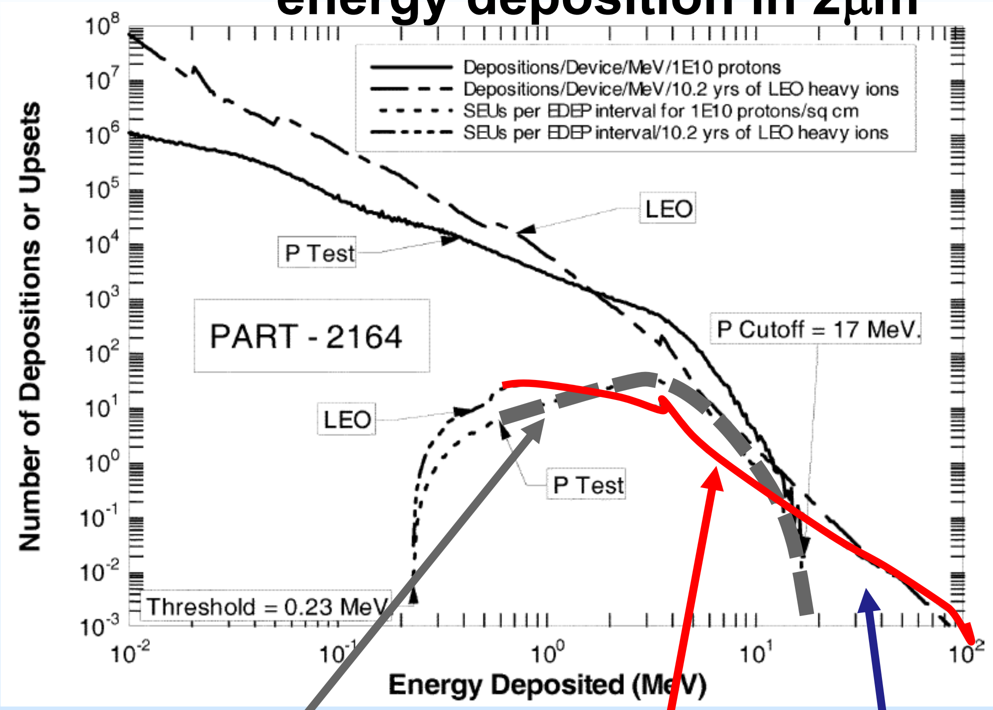


Events during proton testing

Events during 10 year ISS mission

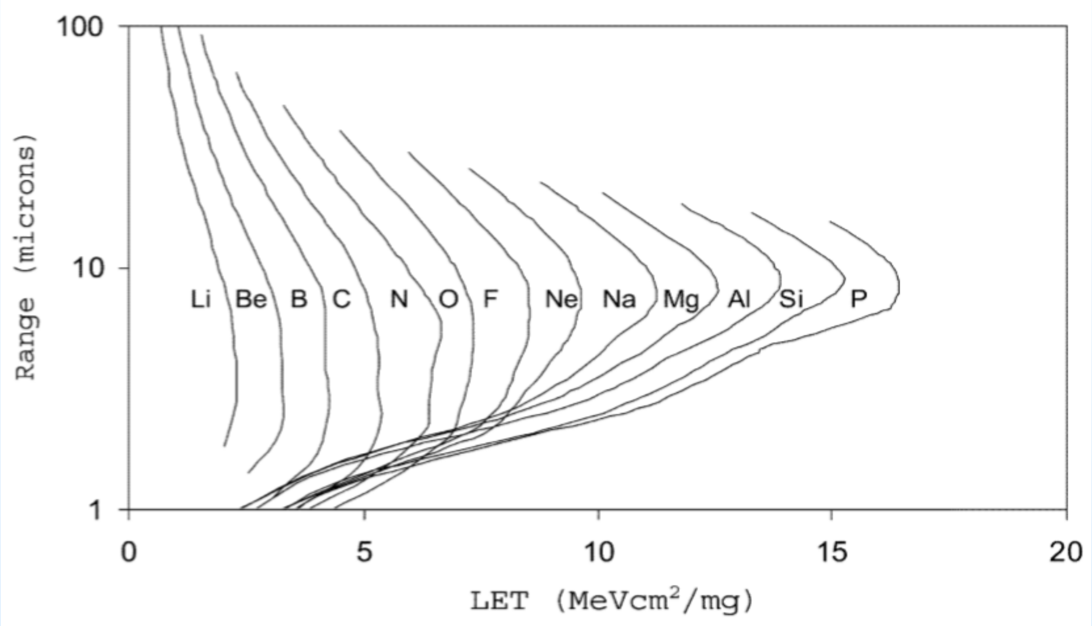
Gap

Similar to LET 14 – but not actually LET

Why 200 MeV?

- **Protons are a proxy for heavy ions because their secondaries give LETs in excess 14 MeV-cm^2/mg.**
- **The higher the energy of the beam, the higher the energy (not LET) of the secondaries.**
  - **Total deposited energy is higher, so they are more space-like.**
  - **Actual energies form a distribution…**
  - **Increased range improves damaging SEE effectiveness**
  - **Higher LETs in space are mostly Fe – missing in proton secondaries…**
  - **Are there enough secondaries to get coverage/assurance?**

Hiemstra, 2003 – for 500 MeV protons



- **But > 200 MeV is not readily available, and doesn't really improve things much.**
  - **Max LET is still only around 14 MeV-cm^2/mg**
  - **Overall range is better**
  - **Options like Los Alamos (800 MeV), TRIUMF (500 MeV), CERN, and PSI exist.**

200 MeV Is a Sweet-Spot, but…

- It is good for proton secondaries.
- Higher proton energy also reduces dose.
- It puts SEE test facilities in-line with medical facilities.

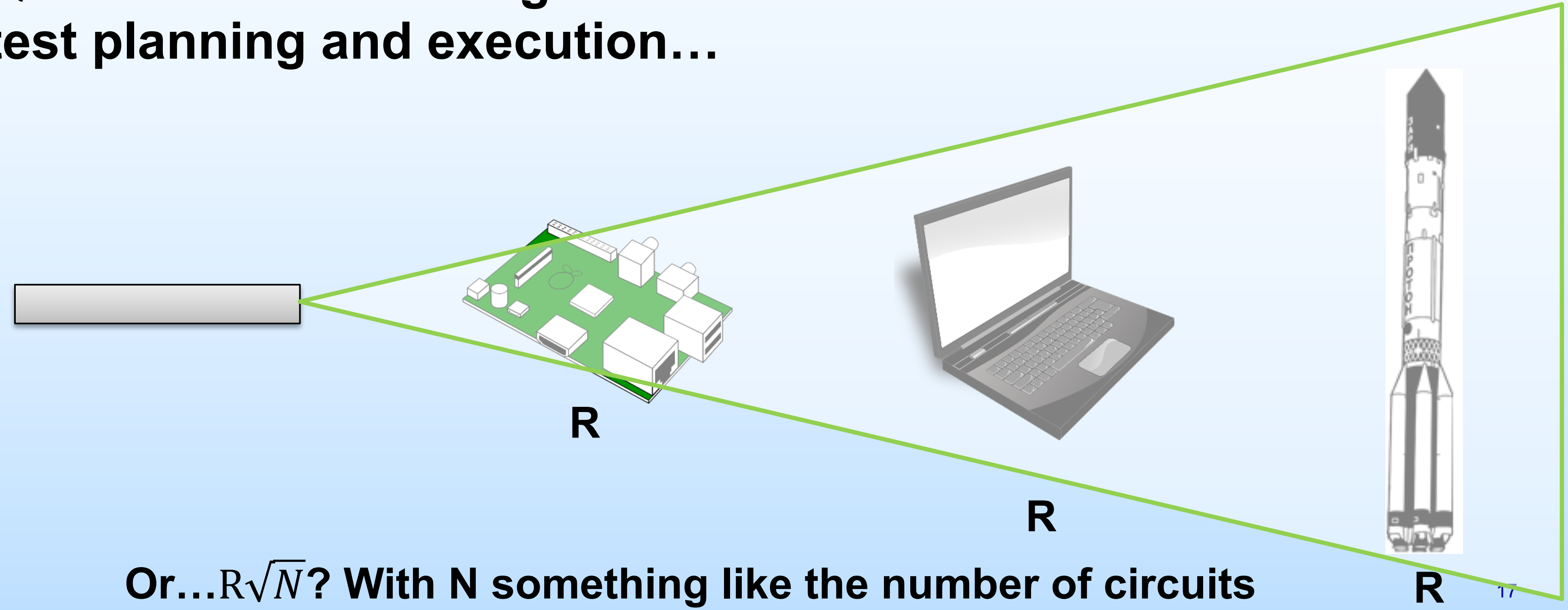
California Protons
CANCER THERAPY CENTER

MAYO CLINIC

- Dozens of facilities…

There Are Many Potential Issues

- **Test results are not well-defined, because system size can be arbitrary**
  - **Assume the test results in a system rate of R…**
- **Questions arise throughout the test planning and execution…**



Or…$R\sqrt{N}$? With N something like the number of circuits

Scorecard

- The proton board-level testing method has a history of success
- But it is not supported by solid engineering or physics

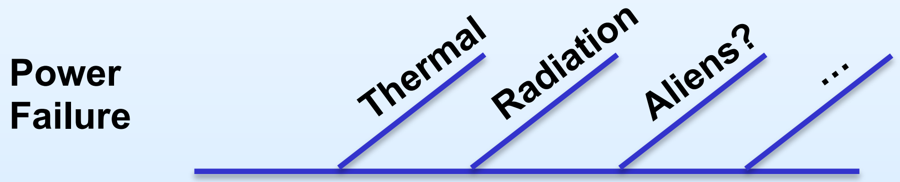
- Have previous practitioners have been conservative in using the approach?
  – Maybe
- Have we been lucky that systems worked well?
  – Probably. Might even be “accidentally” mitigating damage
  – NASA has only used this in non-critical systems
- Have some failures not been reported?
  – Difficult to say on the NASA side – probably logged, but not necessarily brought to attention of radiation people
  – Suspect situation is worse in most other organizations

Pragmatic Approach – Data Driven

- If you don't use the hard engineering and science limits, which are terrible…
  - The other approach is to be pragmatic – see how it does
- What type of data do you need to support or refute the test approach?
  - Heavy ion data with LETs between 2 and 15 MeV-cm^2/mg
  - & Proton data
  - The critical dataset is devices with:
    - Proton failures that can be correlated to heavy ion failures
    - Lack of proton failures but with heavy ion failures with an established space rate
    - No proton or heavy ion failures

Pragmatism – The Danger

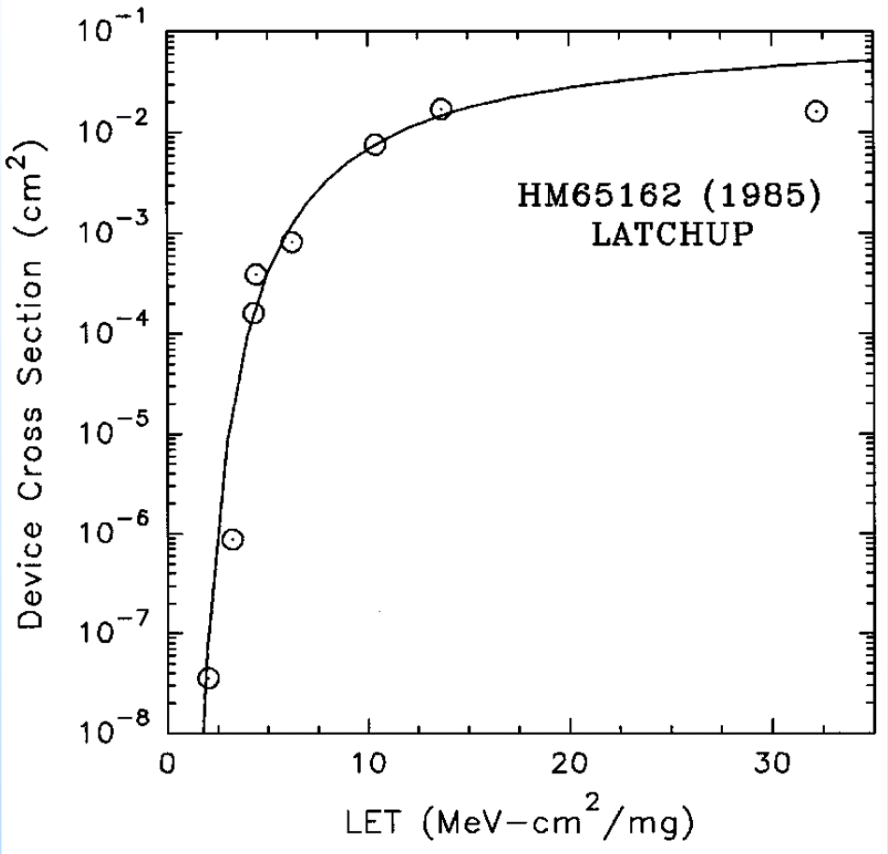
- When the method has been used
  - JSC has used for low criticality items on the ISS
    - Not mission critical, and astronauts can disconnect
  - Has been OK? Has it?
    - These are low budget programs… other unhanded failure elements could be there
      - Determining failure root cause can be difficult



  - Or have failures not been reported?
    - It can be expensive to figure out… maybe just cut the loss?
- How would you show it is bad?
  - Distribution of parts you might test vs proton and heavy ion data.
    - But nobody collects this data

Example of a Bad Part

- How bad can the "gap" be – what's missed by a $1\times10^{10}/cm^2$ proton test
- One example bad part is the HM65162 (1985) SRAM



- Has SEL at very low LET
  - Energy cutoff discussed above suggests SEL should be seen
  - Actually has ~40% of no SEL in $1x10^{10}/cm^2$ protons
  - Since threshold is low, more protons gives higher chance of seeing SEL. $1x10^{11}/cm^2$ @ 200 MeV (6 krad[Si]) gives >99%
  - But here we know the curve…
- ISS SEL rate is about 0.01/device-day
- Similar observation - NEC4464

Nobody Takes this Data

- If you take heavy ion data first
  - The part would have to fail with an LET below 8 MeV-cm^2/mg or have no failures to be of interest
  - If the program is serious enough to take heavy ion data:
    - Failures mean part is eliminated, proton data is not needed
    - No failures mean proton data is not needed
    - Special case: The part fails under heavy ions but the project is desperate and wants to know how bad it is…
      - Remove conservatism in bound for proton sensitivity
- If you take proton data first
  - Program is interested in things like displacement damage
  - Program is just testing for protons – no heavy ion data will be taken
  - Special case: Maybe it was just a timing thing, as part of a complete dataset…

Test Planning - 1

- Test a copy of the flight board – same parts – manufacturer and part number should match.
  - “good engineering” says they really need to be the same, but people are often trying to justify “similar devices”
  - SPARTAN flights actually flew irradiated hardware (RADECS ‘98) – Not Recommended
- Reserve beam time 8 months ahead of time. Proton beam time is difficult to schedule.

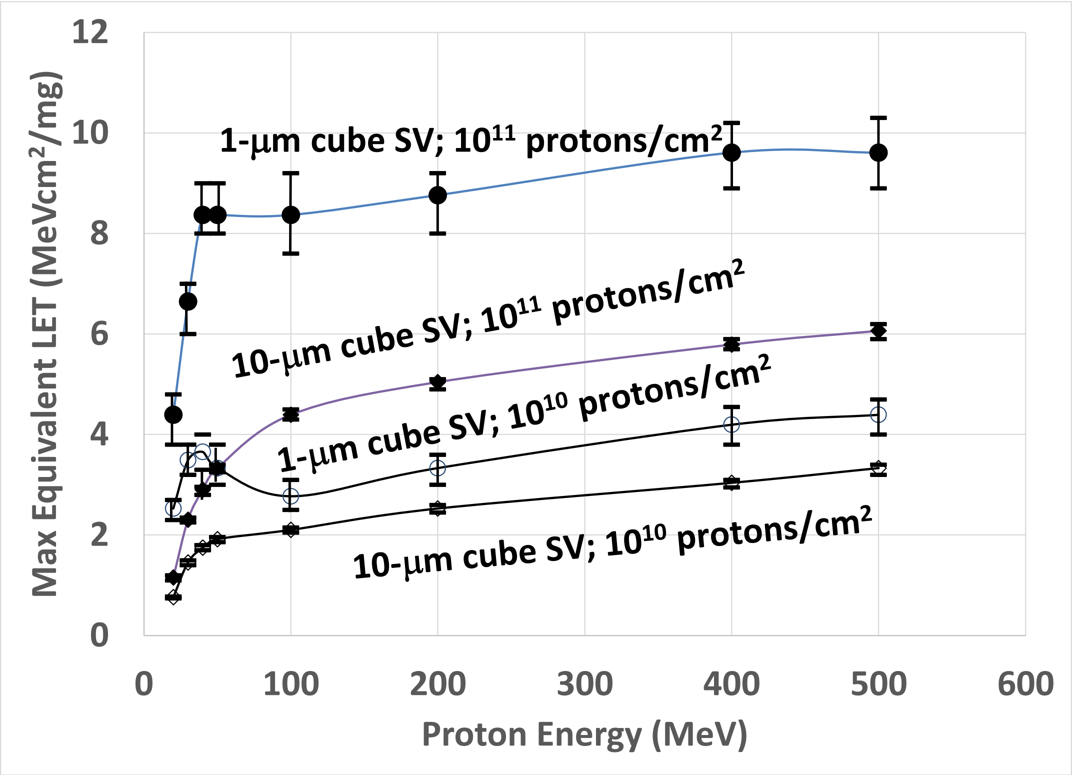
- Use beam energy of at least 190 MeV in order to keep TID on articles below 1 krad(Si) when irradiating to $1\times10^{10}/cm^2$.
  - Determine if $1\times10^{11}/cm^2$ may be better for your situation (only buys about 3x better results for SEL, SEGR, SEB)

Test Planning - 2

- You can only reliably achieve 0.01-0.003 damaging events per system day in LEO – if this is not good enough, heavy ions are required. (NEPP Board Proton Testing Book of Knowledge)
  - Higher assurance claims are not grounded in physics or engineering, but may "seem" to work.
- Test early in the cycle, so the results can be used. Don't just hope the results will be ok.
  - Normal RHA flow, but often missed for this approach.

Test Planning - 3

- There are some parts with failure rates around 0.1/device-day in ISS orbit. You're here without test data.
- Test boards must use the same devices as flight units
- With proton testing, $1e10/cm^2$ results in DSEE rates around 0.01/device-day
  - 1e11/cm2 improves this, but hard numbers are limited
- Must consider exposure level and SEE types
- If possible plan to use two energies to enable use of Bendel 2-parameter



–Ladbury, IEEE TNS, 2015

Equivalent LET = Energy / (ρ*d_{SV})

Max Equivalent LET requires 2.3 recoils

Facilities

- For proton-only testing, 200 MeV is heavily desired. (Required to meet claims given in guideline.)

Facility	Location	Type	Energy, MeV	Availability
Tri-University Meson Facility	Vancouver, CAN	Cyclotron	480	Ok, but 4x/year
Slater Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)	Loma Linda, CA	Synchrotron	250	4-8 weeks?
Mass General Francis H. Burr Proton Therapy (MGH)	Boston, MA	Cyclotron	235	Booking 8 months out
NASA Space Radiation Lab (NSRL)	Brookhaven, NY	Synchrotron	2500	Ok, but $$

- Ideally, synchrotrons would be avoided due to beam structure impact on testing
- Other proton facilities are available, but require direct communication/discussion for each user

Test Preparation - 1

- Contact facility to get details and recommendations for use of the facility.
- If possible, perform a walkthrough of the facility a few weeks before the actual test.
- Discuss beam parameters with the facility: time and space structure, flux & flux range, etc.
- Determine if the facility can accommodate the full size of your hardware.
- Hardware usually cannot ship for at least a few days after the test.
- Test the full setup (including full cable length) before arriving at the facility.

Photo: Irradiation of iPad at UC Davis – due to spot size, multiple irradiation sites were necessary.

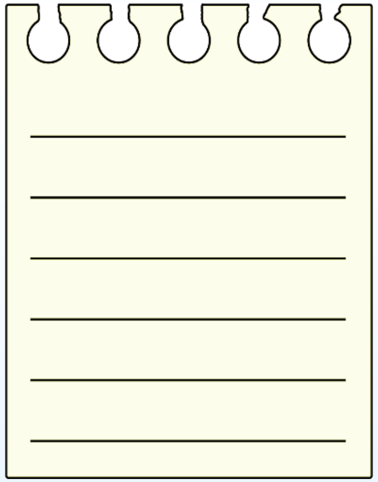
Test Preparation - 2

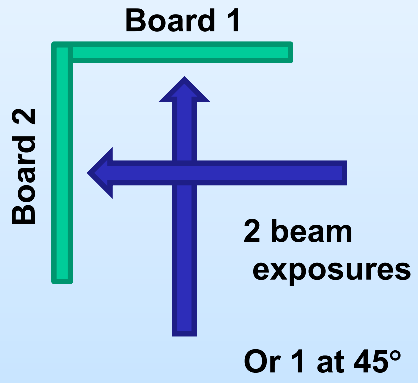
- Test boards/equipment
  - Remove bulky heatsinks
  - Remove/don't install shielding (we're not testing the shielding predictions)
  - Limit beam exposure of any non-test equipment
- Work with facility regarding shipping – especially to Canada
- During exposure, all items in the beam will be exposed to TID
  - Generally, TID levels over 3 krad(Si) are likely to cause problems with boards (but it could happen lower) – **Be careful of unit TID limits!**
  - $1\times10^{11}/cm^2$ is the only viable higher proton limit – requires multiple boards
    - This is only about $1\times10^5/cm^2$ recoils – which is not at the level of a viable heavy ion test.

Proton Energy	Dose for $1\times10^{10}/cm^2$	Dose for $1\times10^{11}/cm^2$	Dose for $1\times10^{12}/cm^2$
50 MeV	1.6 krad(Si)	16 krad(Si)	160 krad(Si)
100	0.94	9.4	94
200	0.58	5.8	58
500	0.36	3.6	36

Test Execution - 1

- Keep a test log including:
  - run number
  - DUT/UUT identification
  - time, fluence, flux
  - etc…
- Use cooling fans instead of heatsinks (keep fans out of beam) – if possible
- Avoid stacks of 6 or more boards
- Test with proton beam normal to the test boards
  - If boards are mounted 90 degrees to each other, test multiple units with beam normal to the board surfaces
  - If angles are used, multiply the fluence delivered by the cosine of the angle of incidence.
- Use beam exposures with duration > 60 s, with at least 10 s between events, or consider slowing down the beam.



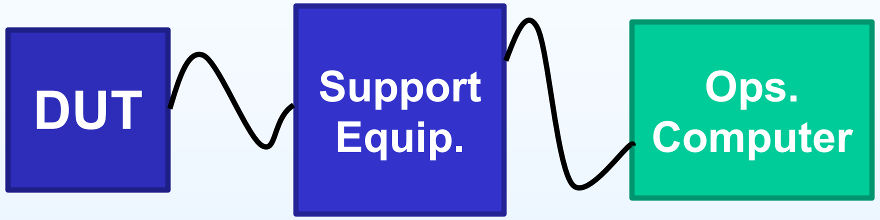


Test Execution - 2

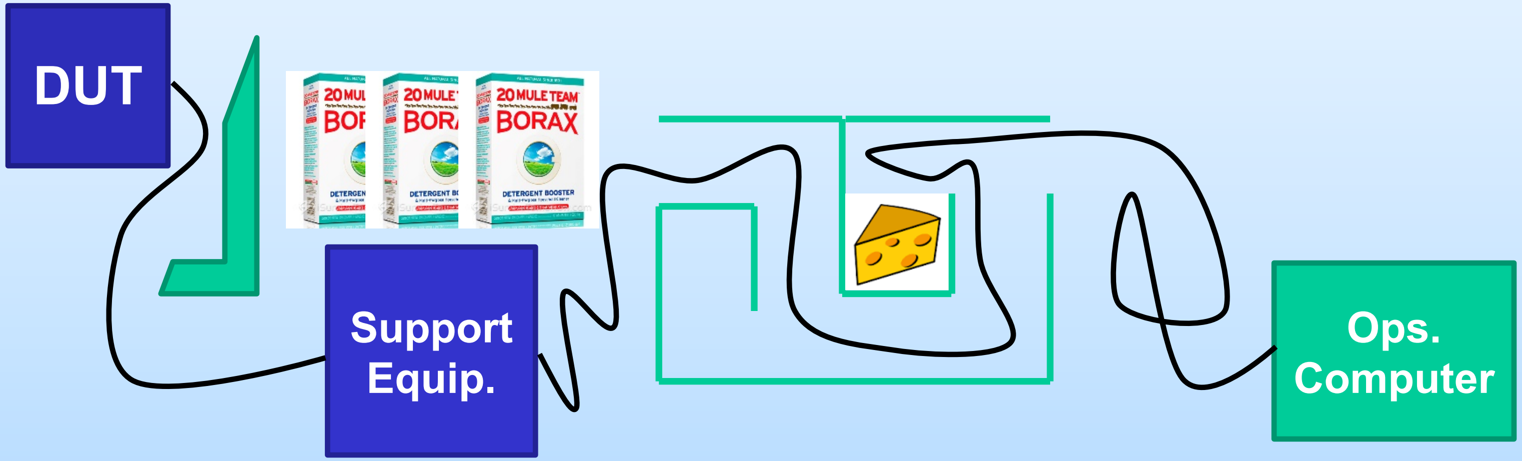
- Verify the beam details by requesting beam diagnostic information from the operator
  - Radiochromic film, scan information, or other
- Be cautious about collimation with brass/copper vs. magnetics. Collimators produce neutrons.
  - Facility may be focused on TID, but you care about neutrons…
- Ensure the test board(s) are positioned far enough away to expose all electronics.
- If multiple boards are used, may want to put Radiochromic film between each unit
  - But it measures dose, not particle fluence…

Test Execution - 3

In the lab…



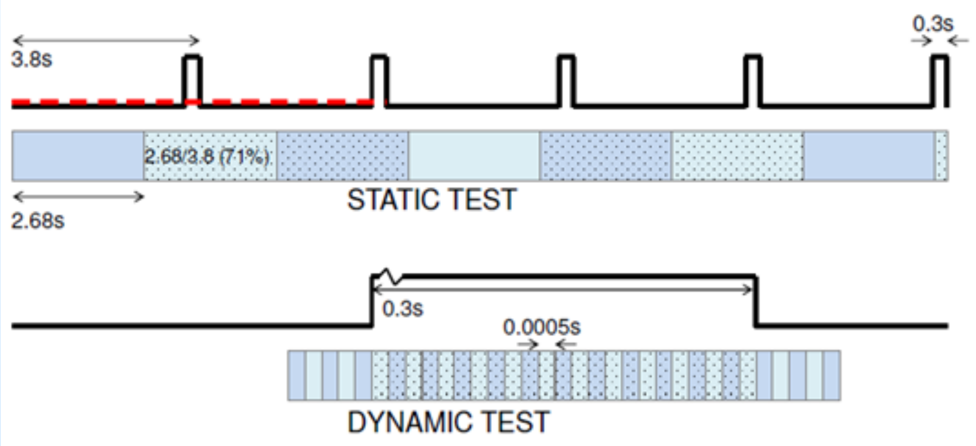
At the facility…



- **Verify test equipment to be used on-site**
  - At home & on-location
  - Cables!
  - Shipping damage

Test Execution - 4

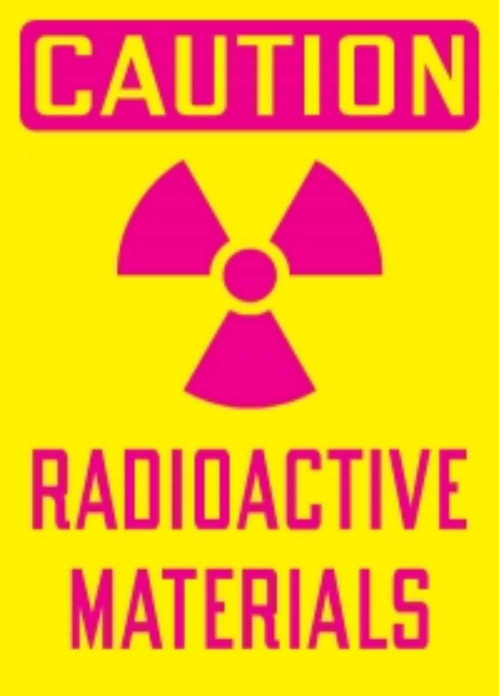
- Operational test modes should be considered carefully
  - Test for normal system response (flight-like application) and recovery (if possible stop the beam during recovery)
    - Typically doesn't have good prognostics or diagnostics
  - Designs specifically for an accelerated test (design for test)
    - Identify errors and increase coverage – but requires careful development
- Try to observe as many error modes as possible
  - Strange, rare event types my be dangerous
    - If there is something rare that may cause a big operational problem, it is more important to study than 100s of events that are easily handled
  - But they may be test artifacts



–Guertin, RADECS Workshop, 2012

- Test operations should keep in mind the beam structure – i.e. synchrotron vs. cyclotron
  - For static tests, beam structure only really causes problems with figuring out live time.
  - But for dynamic tests, it is important that the test does not alias with the beam delivery…

Finish Up



- Be prepared to not have your equipment for a couple weeks due to activation
  – Will be worse with higher energies and higher exposures
  – Shipping regulations vary, discuss with the test facility
- Ideally, a post-irradiation burn-in may help identify latent damage
  – You are not instrumented for a real SEL test!
- All observed error types should be documented before leaving the facility
- Obtain test logs, exposure information, and ensure any shipping or facility exit requirements are handled.

Test Interpretation/Reporting

- It would be great to have a detailed test report, but a simple summary of the test and observations should be a minimum

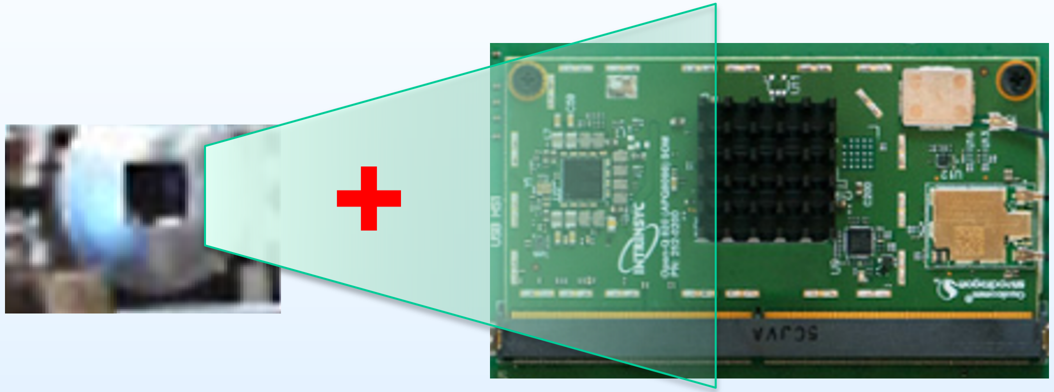
- If damaging events are NOT SEEN, use the following estimations:
  - 0.01 events/system-day for $1\times10^{10}/cm^2$ or
  - 0.003 events/system-day for $1\times10^{11}/cm^2$

- For non-damaging events (transients, bit upsets, etc.)
  - N * 0.0005 events/system-day for $1\times10^{10}/cm^2$ where N is the number of observed events.
  - This scales for higher test fluences.

- If damaging events are seen, use the larger of estimates above.

Lesson Learned:
Plan for a Failed Test

- **Actually, this seems to be the lesson that is never learned… this happens all the time.**



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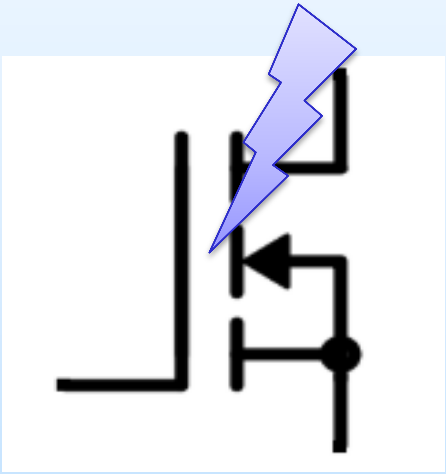
- **–Smoke/**
- **–Explosion**

- **What do you do?**
- **Many programs tell us they have to use it anyways…**
- **But this means you have to know, when planning, how you will handle a failed test.**
  - **Usually programs don't know, but are tolerant of high mission failure probability. Are you?**

Lesson Learned:
Be Ready to Use Test Results

- During one board level test, a permanent failure was observed.
- Because the schematics were available, and a radiation expert (familiar with parts list reviews) was on hand…
  - A list of at-risk parts was identified
  - List was narrowed down by circuit implementation
  - Further narrowed down by failure (no power delivered)
- Identified a MOSFET operating at >80% of rated Vgs in the design
  - Recommendation is < 50%
  - Circuit testing showed the MOSFET had failed
- Were able to swap in alternate (with higher Vgs) that enabled system to work and not fail in radiation.



Lesson Learned: Flight-Like Operation

- Test approach was to have all board operations cycled through during exposure
  - Complex applications made to target all board operations – multiple applications
- The board was dependent on a commercial PowerPC processor running Linux, with the operations in a test program.
- Actual observations were primarily kernel panics due to unhandled exceptions.
  - No additional value was obtained from different software applications
- None of the special test applications showed SEEs because operating system was primary weak point.
  - The exception that proves the rule - test with flight-like OS
- Lesson: Don't develop a lot of extra test operations outside of flight use
  - At least until you know general behavior

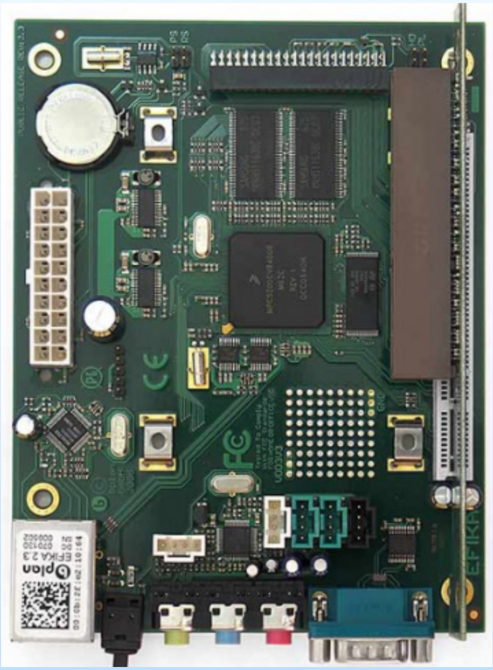


Photo: Efika 400MHz PowerPC SBC

Moving Forward

- Approach is driven by data on worst parts – is there really enough data yet? Most likely no.
  - Why would anyone take proton data on a part that is observed to have SEL with an LET of less than 10?
  - Why take heavy ion data in a part that has SEL observed with protons?
  - Can we press people to take this data and build a dataset?

- Given the inherent limitations of the method, how can we achieve the best results?
- Is there a viable way to test to very high fluence?
  - Generally speaking, we don't think $1 \times 10^{12}/cm^2$ is viable – especially for assemblies / boards due to dose and # of boards.
  - But these are cheap – many devices could be tested cheaply.

- Board-level testing provides a means to explore system-level errors due to radiation.
  - This is becoming very difficult to model from the component level

Summary

- Proton testing can be used in lieu of normal assurance (including heavy ions) if
  - Environment is weak (i.e. LEO, ISS, Mars Surface)
  - Mission is short or can handle high risk
  - You are OK with only having a data point on performance and not really achieving hardness assurance.
- Physics and engineering both suggest fairly high rates for possible damaging SEE
  - 0.01 to 0.003/system-day for ISS orbit when testing with 1×10^{10}-1×10^{11}/cm^{2}.
- To ensure the test method provides results that can be trusted to these levels, we provide recommendations.
  - Test Planning
  - Test Preparation
  - Test Execution
  - Text Interpretation/Analysis

Acknowledgement

- Special thank you for many useful discussions with Ray Ladbury and Ken LaBel.
- Also thanks to many people who either directly or indirectly influenced how I approached or interpreted this topic.
- And special acknowledgement to the commercial entities, CubeSat, and other small satellite groups pushing to re-evaluate these methods.